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Innovation for sustainability: The impact of R&D spending on CO_2 emissions☆

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ABSTRACT

In recent decades the sustainability of economic growth has become a critical objective for most world economies. To achieve this objective it is necessary to stabilize or reduce Green House Gas emissions, which involves making a transition to a low or zero carbon production system. Within this framework, innovation has emerged as a key factor in achieving an efficient energy market and, at the same time, ensuring the sustainable development of any economy.

The main objective of this work is to empirically verify that efforts in innovation have a positive effect on reducing CO_2 emissions. To this end, an econometric model has been estimated. The scope of this work includes the European Union (15), the United States and China between 1990 and 2013. The estimate is performed using a linear regression by ordinary least squares using as independent variables the expenditure on R&D and the energy consumption.

The results of the model support the hypothesis that spending on research and development contributes positively to the reduction of CO_2 emissions for developed countries. Regarding the regions, the corrective effect in the European Unión (15) compared to the figures in the United States is highlighted.

With regard to energy consumption, the results show that this variable is linked to the growth of CO2 emissions so that increases in energy consumption translate into an increase in emissions. Again, European Union (15) is where the effect of this variable is the lowest, followed by the United States where energy consumption is more polluting. The results obtained for China are quite different, due to its economic and environmental performance.

The results obtained provide additional arguments for public policy makers to promote research and development expenditure, both public and private. Since the net effects of innovation translate into a reduction of emissions, this appears as a suitable tool in the fight against climate change. In addition, our study highlights the need to reinforce measures to achieve a decoupling between energy consumption and emissions.

In conclusion, this work shows that R&D spending can be recommended, not only as an engine of economic growth of any economy, but as a driver of sustainable development, where growth can be reconciled with lower CO_2 emissions.

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1. Introduction

In recent decades the sustainability of economic growth has become a critical objective for most of the world economies. Achieving this objective involves, without any doubt, to the stabilization or reduction of Green House Gas (GHG) emissions. This implies making a transition from economic activities based on highly polluting energy sources to sustainable economic activities based on technologies and consumptions with a lower environmental impact (Foxon, 2011; Stern, 2007). It is necessary a technological change that would enable a comprehensive response to climate change without sacrificing economic growth, but how can we make this transition possible?

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One of the most important mechanisms to achieve this structural change is innovation.[1] Schumpeter (1934) stated that economic development is driven by innovation. However, it was after the work of Solow (1957), when innovation and technological development took an increasing role in the economic literature as a determinant of economic growth. In the theory of economic growth, there is abundant literature linking economic growth to the accumulation of knowledge either through learning or investment in research and development (R&D) (Romer, 1986, 1990; Young, 1991; Grossman and Helpman, 1991; Aghion and Howitt, 1992). According to the model of endogenous economic growth, the sectors of R&D create technological innovation with the use of human capital and the stock of existing knowledge (Romer, 1986). In fact, economic theory considers the accumulation of R&D to be essential for economic growth.

But from an environmental perspective, economic growth based on consumption of fossil fuels is closely related to environmental degradation. Since the nineties, most empirical studies (Grossman and Krueger, 1991; among others) analyse the relationship between economic growth and emissions by a function in an inverted U shape, which is called Environmental Kuznets Curve (EKC).[2] For a complete survey of literature either supporting or not supporting the EKC hypothesis, see Dogan and Seker (2016). However, empirical results about EKC are inconclusive.

The effects of technological progress on the evolution of the relationship between economic growth and environment have been explained by the endogenous growth theory, which considers that production processes are improved by increasing the capacity of replacement of polluting resources with other resources which are more environmentally friendly (Stokey, 1998; among others). These models are based on a society committed to the environment, that could invest more resources for protection as their income increases. If emissions decrease as income increases, technology will play a key role and the cause of the reduction in emissions would be the “induced innovation” in the sense of Hicks.[3] Several studies consider that the “induced innovation” is implicit in the hypothesis of the EKC so that its compliance depends basically on the technology (Andreoni and Levinson, 1998; Cantos and Balsalobre, 2013; Balsalobre et al., 2016).

Another question that arises in this context from the environmental policy perspective is whether spending on R&D can be taken as a driver of a less polluting economic growth. In recent years, the broad consensus reached about technological change being the path to achieving sustainable development has caused a great interest in innovation and its promotion, involving most economic agents. In this context the question to ask is what is the effect of technological innovation in reducing emissions? There have been many studies carried out in the energy sector, both at sectorial and at national levels. Almost all of them have been focused on analysing the effect of R&D spending on energy sector on environmental correction, but they have paid little attention to the impact that aggregate R&D can have in reducing emissions.

According to what has been previously stated, innovation is the key variable for the economic growth and its final effect on the environment could be unclear. On the one hand, a higher level of economic activity would lead to higher levels of energy consumption and, maybe, pollutant emissions. On the other hand, an innovative process can be less energy consuming and less polluting. The question would be to know the final net effect. Besides, all these processes take place in every single sector of activity, not only in the energy sector, as energy lies in every one of them. Therefore the innovation is relevant and should be taken into account at an aggregate level. This paper aims to fill this gap in the literature examining the influence that aggregate R&D spending can have in reducing the level of greenhouse gas emissions and therefore in achieving sustainable growth.

Our hypothesis is that although the energy sector is responsible to a great extent of pollutant emissions,[4] the other economic sectors must also be involved in environmental improvement. The aim must be to achieve a reduction in absolute terms, not only in relative terms, of pollutant emissions so that involvement of individuals, businesses and public administrations is necessary for achieving sustainable long-term development.

Moreover, innovation is a public good, with particular features that make its effects neither unidirectional nor direct. In fact, the efficiency improvements resulting from innovation and technological development do not always result in lower consumption of resources and energy. On the contrary, they can lead to a significant increase thereof, the so-called “rebound effect”. This fact reduces the positive effect expected. Moreover, innovation in a broad sense can have positive effects on different sectors from those in which the initial innovation occurred, the so-called “spillover effects”, which would increase the positive impact of innovation. Those effects are of great importance. This gives us a macroeconomic view of how and with what intensity is affecting that variable on the environment and, therefore, on the sustainable development of the economies.

In an effort to take into account all the (positive and negative) effects of innovation on environmental performance, in this paper we consider the aggregate spending on R&D as a determining variable of pollutant emissions. It is necessary to consider that the effects of R&D spending on the economy will take place a few months or even years after the actual spending occurs. For that reason, it will be crucial to introduce that variable with a temporal lapse. This will be discussed later.

Innovative processes lead to activities and products that are more energy efficient and less resource consuming. Therefore, more respectful with the environment. That is to say, it does not matter in which sector the innovation is carried out since in the end it will always be beneficial for the environment.

The aim of this paper is to analyse the effect that aggregate spending on R&D has in reducing CO_2 emissions between 1990 and 2013 in three regions, representing each of them a different way to

[1] According to Oslo Manual “An innovation is the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organizational method in business practices, workplace organization or external relations.” (OECD., 2005, p. 46).

[2] The hypothesis of the Environmental Kuznets Curve argues that the relationship between income per capita and emissions can be represented by an inverted U, so that in a first phase emissions would have a growing relationship with income up to a critical level of per capita income, from which emissions decline as further increases occur in income.

[3] Hicks (1932) distinguished between “autonomous” and “induced” innovation (p. 156–162). The former is exogenous, the latter is endogenous to economic forces. He proposed that a change in the relative prices of the factors of production is itself a spur to invention, and to an invention of a particular kind—directed to economizing the use of a factor which has become relatively expensive. Therefore, if the technological effect is strong enough to cause total pollution to decline systematically between countries as per capita income increases, then induced innovation is probably the cause. The market signals can contribute to this induced innovation process. For example, the increasing costs of resources can encourage a technological change that, in an induced way, favours the conservation of the environment. Likewise, a "green" consumer demand may prompt companies to adopt clean technologies.

[4] As two-thirds of total greenhouse gas emissions and 80% of CO_2 comes from the energy sector, any effort to reduce emissions and mitigate climate change must include the energy sector (IEA, 2015). Given the relevance of CO_2 emissions, we refer to them when talking of GHG in this paper.

deal with environmental problems, besides having different levels of development: the European Union 15 (EU-15), the United States (US) and China. To do this, an econometric estimation by ordinary least squares (OLS) has been performed, for each of the regions considered. From the results obtained from these estimates, we expect to obtain evidence on the need to further promote spending on R&D in all economic sectors in order to reduce environmental pollution.

Spending in R&D is not the only variable used in economic literature as a measure of innovation. It is possible to find works that use the number of patents as an explanatory variable. In this paper, the total aggregate level of R&D expenditure has been used for several reasons: first, because of the available data for the three regions considered in the study; second because of the macroeconomic approach of the paper, which tries to find results in which policy recommendations should be based on; and finally because all the similar papers that analyse the energy sector use the R&D expenditure on that sector. These can be regarded as a complementary line of research to the one presented in this work.

Regarding the geographical areas, with its heavy dependence on coal, China has had the most carbon-intensive energy supply among all regions for the past two decades. Coal has comprised around three-quarters of China's electricity generation mix since 1990. In 2014, China had one of the most coal-dependent power sectors in the world, with coal accounting for over 70% of total generation (IEA, 2016).[5] The United States is increasingly committed to the protection of the environment (at least during Obama's presidency) although it is one of the most polluting economies among developed countries. Finally, EU-15 has a strong commitment to the Kyoto Protocol and is following a clear path to decarbonisation.

The paper is structured as follows. After this introduction, the literature review is presented. In Section 3 the data sources and main statistics are described. The following section explains the econometric model and discusses the results obtained. Finally, Section 5 presents the conclusions.

2. Literature review

Technological innovation as a mechanism to address the challenges of climate change and achieve sustainable development has acquired an important role in the economic literature in recent years, particularly in the energy field (Costa Campi et al., 2015a; Sayegh et al., 2017). Some contributions have focused on examining the process of technological change (Popp, 2010; Sachs et al., 2016). Others study the optimal type of energy technologies that can be used to meet the demand for electricity, taking into account economic and environmental parameters (for the case of China see Cheng et al., 2015; for the Greek case, see Koltsaklis et al., 2014; Koltsaklis et al., 2015; Koltsaklis and Georgiadis, 2015; for Belgium, see Delarue et al., 2009). Christodoulakis et al. (2000) focus more specifically on the inclusion of natural gas in the Greek energy mix and the changes in energy consumption and CO_2 emissions caused by the Community Support Framework Program II.

Determinants and barriers of innovation have also been widely discussed. The debate focuses on two different approaches: one economic and one technological. The first one argues that public policy should only deal with market failures such as imperfect information, spillover effects of R&D, or agent-principal problems among others (Sutherland, 1991; Jaffe and Stavins, 1994). The technological approach argues that public policy must address all the difficulties, whether these market failures or not, such as bounded rationality and uncertainty among others (Brown, 2001; Hirst and Brown, 1990; Palm and Thollander, 2010; Trianni and Cagno, 2012). The most recent literature highlights the need to implement policies aimed at reducing and/or eliminating all types of barriers and market failures (Backlund et al., 2012). Thus, many papers have studied the multiple reasons why many sectors do not carry out innovations (Jaffe et al., 2000, 2004; Linares and Labandeira, 2010; Newell, 2010; Popp, 2010; Del Río et al., 2011; Horbach et al., 2012; Costa Campi et al., 2014).

Some empirical studies have highlighted the importance of the adoption of environmental objectives by firms as they influence the innovation process both directly and indirectly (Jakobsen and Clausen, 2016; Leiponen and Helfat, 2010). In this line, Costa Campi et al. (2015b) analysed the extent to which innovative firms pursue improvements in energy efficiency as an objective of innovation. Their results for Spanish manufacturing firms show the importance of the size of enterprises for innovation in energy efficiency. In addition, they found that companies that aim innovation toward reducing environmental impacts are more likely to innovate in order to increase energy efficiency.

Other studies analyse the evolution of energy intensity and whether or not it converges among countries or regions, arguing that reducing inequalities in energy intensity can be attributed to energy efficiency improvements (Duro et al., 2010; Duro and Padilla, 2011; Mulder and de Groot, 2012; Liddle, 2009). Mendiluce et al. (2010) identify the main factors that determine the evolution of energy intensity: the changes in the economic structure and the changes in the energy intensity of the economic sectors. Fisher-Vanden et al. (2004) argue that the innovative effort is an element that contributes substantially to the reduction of the energy intensity in the business context; generally speaking, this idea had already been considered by Porter and Van der Linde (1995). The decomposition of the structure of energy consumption and its relation to the level of public spending is addressed in Yuxiang and Chen (2010). More recently, studies that have attempted to empirically link GHG emissions with the innovative efforts of economic agents, measured by R&D, have taken a special interest. So, Ruiz (2010) analysed the relationship between the public resources devoted to energy research and the levels of energy intensity observed in the EU-15 countries between 1974 and 2007. To do so he made a Granger causality analysis by specifying a model error correction. The results show that in the long run there is a two-way causality between energy intensity and public R&D in energy, and in the short-term, public funding for energy research contributes to reducing the intensity of energy consumption.

Garrone and Grilli (2010) using panel data for 13 advanced economies in the period 1980 to 2004, analysed the relationship of public R&D in energy with the CO_2 emissions per unit of Gross Domestic Product (GDP) and its two components: the energy intensity and the carbonization factor. The results obtained confirm that public expenditure on R&D is not enough by itself to improve the innovation process. Public spending on energy R&D has been successful in improving energy efficiency at country level but has failed to have an impact on the carbonization factor and the emission intensity. Cantos and Balsalobre (2013), using the Environmental Kuznets Curve model, obtain evidence of the existence of an inverse relationship between public spending on policies of Research & Development & Innovation energy and greenhouse gas emissions for Spain.

Wong et al. (2013) estimated the short-run and long-run elasticities of different types of energy consumption and energy R&D to changes in oil prices and income of the 20 OECD countries over the

[5] For a survey on Chinese environmental policy see for example Chow (2013).

period of 1980-2010.[6] They found negative income elasticity of demand for coal consumption but positive income elasticity for oil and gas consumption suggesting the importance of economic growth to promote the use of cleaner energy. Through dynamic linkages between energy consumption and the energy R&D, they found that fossil fuel consumption promotes fossil fuel R&D, and fossil fuel R&D, in turn, drives its own consumption.

Balsalobre et al. (2016) analysed the impact of economic growth, energy innovation policies and promotion of renewable sources on GHG emissions for 24 OECD countries since 1992 to 2010. They show that government efforts in innovation and energy substitution are associated with a reduction in GHG emissions.

Bosetti et al. (2011) used an integrated assessment model with multiple externalities and an endogenous representation of the technical progress in the energy sector. They evaluated a series of innovation policies, both stand-alone and in combination with other mitigation policies. The findings indicate that innovation policies alone are unlikely to stabilize global emissions. As for the benefits of combining climate and innovation policies, they found 10% gains for a stringent climate policy and 30% for a milder one. Nevertheless, such gains are reduced when more plausible global innovation policy arrangements are considered.

Lee and Min (2015) using a sample of Japanese manufacturing firms during the period of 2001–2010, found a negative relationship between green research and development and carbon emissions, while green research and development was positively correlated with financial performance at the firm level.

In this research line, which tries to empirically link CO_2 emissions to R&D, this work aims to analyse the impact that spending on R&D has on environmental improvements. The novelty of this study lies in the consideration of the aggregate expenditure on R&D as an explanatory variable of CO_2 emissions, which sets it apart from most studies, where generally only private and/or public spending on R&D energy are considered.

3. Data source and statistics

In order to observe whether innovation is acting as a reducing factor in emissions in absolute terms, and if it is doing differently in regions with different sensitivity to global environmental degradation, this work aims to analyse the European Union-15, the United States and China. This study focuses on these three areas because on the one hand, they are the major economic powers of the world and, on the other hand, as previously stated, each one of them faces the problem of CO_2 emissions differently.

These three areas account for over 50% of CO_2 emissions, real GDP, and global final energy consumption for the period considered. The US and the EU-15 fall into the category of developed countries, while China would be classified as developing countries leader, with a GDP growth rate much higher than the other areas of analysis but with a per capita GDP well below.

The source used for environmental and energy data is the International Energy Agency, from the report "CO_2 Emissions from Fuel Combustion Highlights" (2015) for CO_2 emissions and from the energy balances for the energy consumption. As an indicator of innovation, the aggregate expenditure on R&D is used, whose figures are from the OECD (2016), for the three regions considered.[7] All variables used in the estimation are annual data from 1990 to 2013.

The statistical information of the data used in this analysis is presented in Table 1. In relation to the measures, spending on R&D is measured in millions of dollars, purchasing power parity (PPP) basis, 2010; CO_2 emissions and final energy consumption are both expressed in millions of tonnes (CO_2 equivalent and TOE, respectively).

One of the advantages of using carbon emissions is that our research is directly related to the most serious global environmental issue at the moment: emissions of carbon dioxide are considered the driving force of global warming. The Kyoto Protocol (signed in 1997) promotes a decrease in such polluting emissions, but not all regions and countries accept this decline as the most important measure of environmental performance.

In this sense, without entering a comprehensive review and description of their climate change policies, as it is not the object of this work, but it can be said that the attitude of the three regions considered about Kyoto has been very different. This is quite evident in reading a brief review of the position of each region and its commitment to market measures. Specifically, the European Union has not only signed the Kyoto Protocol but it was the first region to launch a multinational market for the CO_2 in 2005, the emissions trading system (EU-ETS). By establishing a price on CO_2 emissions, the most polluting industries would have a strong economic incentive to improve technology. On the other hand, the US, despite having shown interest in reducing pollutant emissions did not sign the Kyoto Protocol. However, it launched the first market of tradable permits for Nitrogen Oxides emissions (NOx) and Sulphur Dioxide emissions (SO_2) in 1990. Currently, various US states have other trading systems of tradable permits on greenhouse gas emissions.[8] In the case of China, who also failed to sign the Kyoto protocol, it must also be considered that it has made clear its priority of getting a high rate of growth at the cost of using fossil energy sources, which are very polluting and have limited supply. This attitude of the Chinese economy has changed dramatically in recent years, possibly because of the serious environmental problems that the country is facing, particularly in big cities. In fact, we are seeing that China has a much more participatory and active role in climate negotiations, as well as an increased environmental commitment, as shows its intention to develop its own market of

[6] There is extensive research on price and income elasticities of energy demand through the use of different tools and models. Fan and Hyndman (2011) make an empirical assessment of price elasticity of demand of electricity in southern Australia. Their results show that the price elasticity varies with the time of day and the time of the year and that the sensitivity of the electricity consumption to the prices in extreme climatic conditions is weak, in spite of the high demand in those moments. Polemis and Dagoumas (2013) analyse the relationship between electricity consumption and economic growth in Greece in a multivariate framework to capture short- and long-term dynamics in the period 1970–2011. Their results show that in the long run, the demand for electricity is price-inelastic and elastic to income, while in the short term the relevant elasticities are below unity. They also argue that the causal relationship between electricity consumption and economic growth is bidirectional and that the inclusion of renewable energy sources would provide significant benefits to ensure the security of supply in the Greek energy system. For the particular case of the elasticity of demand for residential electricity, see among others: Haas and Schipper (1998), who study whether energy demand behaviour is determined by prices and rent in ten OECD countries. Espey and Espey (2004) perform a meta-analysis to quantitatively synthesize the studies of residential electricity demand and determine if there are factors that systematically affect the estimated income and price elasticities, concluding that extrapolating the results of a place or time period to another may not provide an accurate estimate. Silk and Joutz (1997) use cointegration techniques to develop a model of error correction of the annual residential electricity demand in the United States. For the Greek economy, Hondroyiannis (2004) uses a multivariate analysis to estimate the residential demand for electricity in the long term and uses a vector of error correction to study the importance of deviations in the short term.

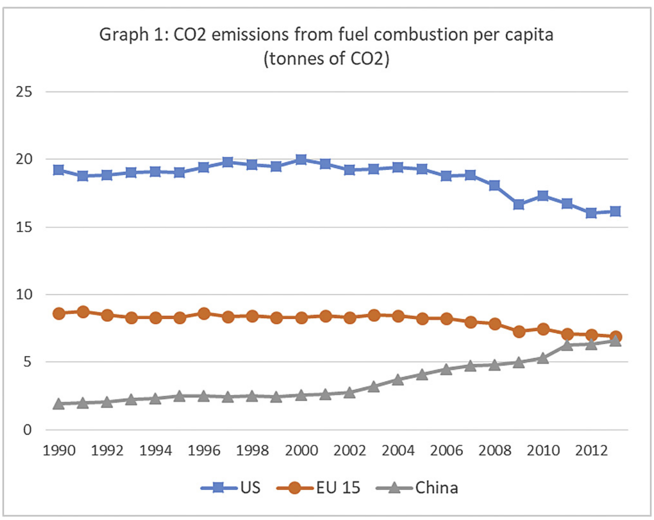
[7] The period of study is conditioned by the expenditure in R&D data, (available since 1990) and for CO_2 emissions data, with no available estimates beyond 2013.

[8] In this regard, please consult the website of the United States Environmental Protection Agency (https://www3.epa.gov/). Because of its smaller size, its smaller scope and that some of them have not started to work until 2012 (e.g. California's Cap and Trade Program), its effect is not relevant to the temporal scope of this work.

Table 1
Summary statistics.

	Mean value	Median value	Standard Deviation	Maximum value	Minimum value	AAGR (%)
CO_2 emissions *(millions of CO_2 equivalent)*						
US	5,306.70	5,376.01	3,05.57	5,702.27	4,765.15	0.28
EU15	2,796.85	2,834.61	133.14	2,938.90	2,491.30	−0.60
China	4,581.23	3,446.20	2,165.44	8,977.10	2,183.57	6.34
Energy Consumption *(millions of TOE)*						
US	1,462.99	1,494.60	92.57	1,576.04	1,293.50	0.67
EU15	990.41	993.01	47.62	1,057.34	904.60	0.27
China	1,066.98	840.66	400.78	1,943.49	664.21	4.78
Total R&D expenditure *(millions of $ PPP, 2010)*						
US	328,958.62	335,918.24	71,406.00	432,583.17	231,004.87	2.77
EU15	237,485.46	240,769.90	43,836.02	305,671.00	183,157.21	2.25
China	92,091.63	51,911.00	92,750.70	316,303.17	11,504.21	15.50

Source: Own calculations using data from IEA (2015) and OECD (2016).



Graph 1.

tradable emission rights for 2017.[9] As the results will not be visible in the short term, it suggests that this is not relevant to the temporal scope of study of this work.

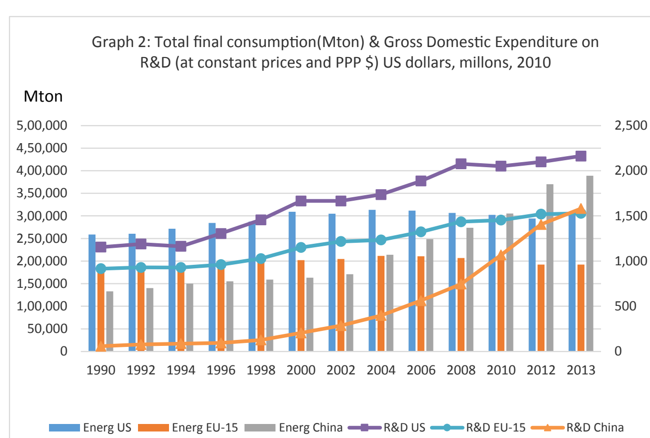
Table 1 shows that the US has the highest average emissions, but in China they are increasing at an average annual rate of 6.34%.

According to figures presented in Table 1, the deviation of all values in the case of China is highlighted. This is consistent with the large difference between the maximum and minimum values of all variables. A spectacular growth is seen in each and every one of the Chinese variables, reaching maximum values similar to those of the EU-15 and the US in all cases. In the case of CO_2 emissions. China's maximum value far exceeds the US and EU-15 data. However, in per capita terms, the US is the most polluting country (see graph 1). CO_2 emissions per capita of US and EU-15 tend to decrease, especially in recent years (AAGR -1.6% and −1.4% respectively); while they are clearly increasing in China, particularly since 2000 (AAGR 7.5%).

The representation of R&D expenditure and energy consumption (graph 2) show the growth of both variables in the case of the Asian economy. China has already outperformed the other two regions in energy consumption, and in the case of R&D expenditure, in the last period, it has equalled R&D spending in the EU-15.

Table 2 presents the correlation matrix between the variables for the three regions, being CO_2, the total emissions of $C0_2$, E, the energy consumption and R&D the total aggregate expenditure on R&D. The correlation is calculated by the covariance between variables.

The CO_2 emissions, the endogenous variable, as expected, shows a positive correlation with the energy consumption in the regions studied. In addition, it shows a positive correlation with spending on R&D. Quantitatively, the case of the EU-15 is highlighted, whose values are lower than those of the other two regions analysed. The correlation between energy consumption and CO_2 emissions for the EU-15 is significantly lower than in the cases of the US and China. This may indicate a less polluting energy consumption in Europe than in the other two regions studied. In the case of the correlation between R&D expenditure and CO_2 emissions, data from the US and EU-15 are lower than those from China. In this case, it seems that in the less developed Chinese economy there is a clear relationship between expenditure on innovation and CO_2 emissions (perhaps because of the effect that R&D has on economic growth through higher consumption of more polluting energy). This argument would be common for the correlation between R&D and energy consumption, whose highest value corresponds to China. Again, spending on innovation leads to greater economic



Graph 2.

[9] See Li et al. (2012).

Table 2
Correlation matrix.

United States				EU-15				China			
	CO_2	**E**	**R&D**		**CO_2**	**E**	**R&D**		**CO_2**	**E**	**R&D**
CO_2	1			**CO_2**	1			**CO_2**	1		
E	0.905	1		**E**	0.312	1		**E**	0.996	1	
R&D	0.476	0.783	1	**R&D**	0.381	0.468	1	**R&D**	0.980	0.990	1

growth that is associated with higher energy consumption, more polluting in this case.

Despite the statistical significance, the magnitude of the correlation between spending on R&D and emissions is relatively low in the cases of the US and the EU-15. This should not worry because the pairwise correlation shows only the relationship between two variables, rather than a causal link.

Spending on R&D shows a positive correlation with energy consumption in the three areas analysed. The magnitude of the correlation is remarkably low for EU-15, although its statistical significance is very high in this case.

In this paper, the aim is to deepen the relationship between CO_2 emissions and the aggregate expenditure on R&D carrying out a regression for the analysis. This kind of analysis has been chosen because of the available data. We work with three regions and a temporal series of three variables (energy consumption, total R&D expenditure and CO_2 emissions). As the number of cases (geographical regions) is low, the best model should be a regression while a panel data analysis is not appropriate.

4. Econometric analysis and results

In this paper, in order to analyse the relationship between CO_2 emissions and the level of R&D spending, an econometric estimation was carried out for each of the countries surveyed since 1990 until 2013. The estimate was performed applying a linear regression by ordinary least squares (OLS). The independent variables are the expenditure on R&D and the energy consumption.

Regarding the independent variables two considerations should be noted:

- The economic growth (in terms of GDP) is typically considered as an explanatory variable of CO_2 emission. However, given the direct link between economic production and energy consumption and the relationship of both variables with CO_2 emissions, it is desirable to use just one of those variables for the estimate, in order to improve the explanatory power of the model. In this paper, the final energy consumption has been used as a variable "proxy" to economic growth.[10,11]
- Most of the empirical studies using the R&D spending include some delay in the variable (Garronne and Grilli, 2010; Brutschin and Fleig, 2016). The intention is to capture the period of time for the impact of spending to become applied technology and eventually to affect the level of pollutant emissions since technological incorporation does not occur immediately. A delay of two periods in R&D spending has been confirmed to be the best for the model.[12]

The model used in this paper to estimate the effect of aggregate R&D expenditure and final energy consumption on pollutant emissions for each of the countries analysed is as follows:

$$GHG_{i,t} = \alpha_i + \beta_1 (R\&D)_{i,t-2} + \beta_2 E_{i,t} + \varepsilon_{i,t}$$

where $GHG_{i,t}$ are CO_2 emissions for country “i” in year “t”, $(R\&D)_{i,t-2}$ is the aggregate R&D spending of country “i” in year “t-2” and $E_{i,t}$ is the final energy consumption in country “i” in year “t”.

This relationship is completed with a constant (α) that collects, for the country “i”, other exogenous effects not included under the R&D spending or under the energy consumption, and the error, $\varepsilon_{i,t}$. The coefficients β_1 and β_2 represent the relative importance of the independent variables when explaining the dependent one.

The series have been taken in logarithms, which allows us to interpret the coefficients in terms of elasticities[13]; the coefficient of each of the independent variables indicates approximately the percentage of variation of the dependent variable when the independent variable changes 1%.

So the model (1) to be estimated is as follows:

$$\ln GHG_{i,t} = \alpha_i + \beta_1 \ln(R+D)_{i,t-2} + \beta_2 \ln E_{i,t} + \varepsilon_{i,t} \quad (1)$$

To estimate the above equation, the ordinary least squares (OLS) method has been chosen, using observations from the period 1990–2013 for the US, the EU-15 and China. The results obtained are shown in Table 3.

For the US, the coefficients β_1 and β_2 are statistically significant and show the expected signs: positive in the case of energy consumption (E_t) and negative in the case of R&D spending ($R\&D_{t-2}$). The model has a high explanatory power, as reflected in the adjusted R squared 0.933694 and a small sum of squared residuals (0.0033), which means that the model explains more than 90% of the variability of the dependent variable, the total US CO_2 emissions. As for the model specification, it is solvent, presenting a Durbin-Watson statistic value of 1.16.

The estimate shows that a marginal increase of one percent in the final energy consumption (ceteris paribus spending on R&D) represents an increase of 1.2% in CO_2 emissions. This indicates a

[10] A previous correlation analysis has been performed, obtaining the following results between energy consumption and GDP: 0.66 for the EU-15; 0.84 for the US and 0.99 for China.

[11] The population, and in particular its growth, is also considered a relevant variable in the explanation of the emissions. This growth is reflected in the GDP and, consequently, the variable energy consumption also reflects the effect of population growth implicitly. However, it should be noted that the econometric models of this work have also been estimated in per capita terms. The results of these regressions are very similar to those of the models presented in this paper, both in the sign and in value.

[12] In some empirical studies that link R&D spending with some environmental variable, it is common to introduce two periods of delay in spending on R&D (see, for example, Cantos and Balsalobre, 2013). In this work, a robustness check has been carried out for different temporal delays (t, t-1, t-2 y t-3), with no important differences in results.

[13] The use of natural logs for variables in an econometric model is very common, especially to find a linearity among non-linear variables. The practical advantage of the natural log is that the interpretation of the regression coefficients is straightforward. After estimating a log-log model, the coefficients can be used to determine the impact of the independent variables (X) on the dependent variable (Y). The coefficients in a log-log model represent the *elasticity* of the Y variable with respect to the X variable. In other words, the coefficient is the estimated *percent change* in the dependent variable for a *percent change* in the independent variable.

Table 3
Effects of R&D on carbon emissions (model 1).

	US	EU-15	CHINA
	Coefficient (Stand Error)	Coefficient (Stand Error)	Coefficient (Stand Error)
α_i	1.68692**	5.13801***	1.32157***
	(0.402524)	(0.506552)	(0.405724)
β_1	−0.14487***	−0.260182***	0.19075***
	(0.0186626)	(0.0197386)	(0.0402199)
β_2	1.19645***	0.869686***	0.721356***
	(0.0728852)	(0.0776105)	(0.118118)
Sum of Squared resid	0.003305	0.004152	0.024294
Adjusted R-Squared	0.933694	0.913654	0.993153
Durbin-Watson	1.156395	0.569048	0.590950

Confidence interval: *** represents 99%, **95% and *90% confidence levels.

high sensitivity of CO_2 emissions to final energy consumption and, at the same time, low efficiency in energy consumption in environmental terms.

The β_1 coefficient indicates that the elasticity between CO_2 emissions and aggregate expenditure on R&D is negative and less than one. Thus, given the energy consumption, an increase of 1% in R&D spending decreases CO_2 emissions to a lesser extent ($\beta_1 = -0.15$).

The estimated model for the EU-15 has a high goodness of fit (adjusted $R^2 = 0.91$); the coefficients β_1 and β_2 present a high degree of significance and the expected signs. In the case of final energy consumption, an increase of one percent in consumption implies an increase of 0.87% in CO_2 emissions.

The values of parameters show that an increase in energy consumption increases CO_2 emissions in a higher proportion in the US and in a lesser amount in the EU-15.

Regarding the impact that R&D spending has on CO_2 emissions, the coefficient β_1 is negative ($\beta_1 = -0.26$). This indicates that spending on R&D has a positive effect on the environmental correction in the European economy, leading to a reduction of CO_2 emissions independently of the energy sources used.

Innovation, therefore, reduces carbon emissions in the EU-15 and the US in the period considered, which suggests a positive impact of the innovation on the environmental quality of both regions, although absolute values show a much greater effect in the EU-15.

In relation to energy consumption, although the signs of both parameters are positive, the lower increase in emissions in EU-15 reflects a more environmentally friendly energy mix. Europe has clearly opted for clean energy.

The results in the case of China show that spending on R&D strengthens the emitting role of energy consumption in this country, since β_1 and β_2 are positive. The concern for economic development makes innovation geared towards economic growth and increased use of highly polluting energy resources. A change in the Chinese economic model is highly desirable.

It should be noted that the estimates for the EU-15 and China have problems of autocorrelation (Durbin Watson statistic is close to zero).

With the intention of solving this technical problem a new variable has been incorporated into the estimation. CO_2 emissions with a delay of one period ($GHG_{i,\ t-1}$) (Beck and Katz, 2011; Brutschin and Fleig, 2016), resulting the initial specification model in the following one (model 2):

$$lnGHG_{i,t} = \alpha_i + \beta_1 ln(R+D)_{i,t-2} + \beta_2 lnE_{i,t} + \beta_3 lnGHG_{i,t-1} + \varepsilon_{i,t} \tag{2}$$

In order to compare results, the model is also applied to the other region analysed in this work, the United States.

This change aims to include the influence of the past emissions on current ones, which indirectly indicates whether the emissions reduction policy has been effective.

The new model results (presented in Table 4) have improved substantially for the US and the EU-15. In the US, it is clear that there is no autocorrelation, as it shows a value of 0.08 for the Durbin h-statistics. The introduction of the dependent variable with one period of delay has increased the goodness of fit, increasing the value of adjusted R-squared to 0.95.

In the case of the EU-15, this model has improved the overall goodness of fit (measured by adjusted R-squared), which means that the model explains over 92% of the variability of the dependent variable, the total CO_2 European emissions. Durbin h-statistic and the degrees of freedom of the estimation show that problems of autocorrelation have been reduced.

In both cases, the US and EU-15, the coefficients of all the variables are statistically significant at 99% confidence level and they keep the expected sign: positive for the final energy consumption and emissions of the previous period, and negative in the case of expenditure on R&D. The parameters β_1 y β_2 (less than 1) indicate a lower sensitivity of CO_2 emissions to the two explanatory variables (energy consumption and R&D expenditure) with respect to the initial model.

The coefficient for the $GHG_{(i,t-1)}$ variable, β_3, is statistically significant in 99% in the US and 90% in the EU-15. The value of this parameter is very similar in both areas. This may be because CO_2 emissions are worldwide, although their origin is local. The lower level of the European coefficient may be a consequence of EU-15 regulatory policies, which encourage the reduction of CO_2 emissions (see, among others, Fernández et al., 2015).

The specific results for the Chinese economy are inconclusive. They show specification errors that can be observed in the Durbin h-statistic. The process proposed for the correction of potential autocorrelation problems has not been satisfactory in this case. This may correspond to the different behaviour of the Chinese economy from the other two regions considered, characterized by a high economic growth target without concern over emissions. The Chinese economy has long been based on coal, oil and gas, as well as in nuclear power, but the country is also now firmly established as a global leader in renewable energy, efficiency and innovation (IEA, 2017). It will be interesting to study when new data are available if the model offers better results as a consequence of this change in Chinese environmental behaviour.

In summary, both models suggest a reducing effect of aggregate R&D spending on CO_2 emissions in the US and EU-15. The results

Table 4
Effects of R&D on carbon emissions (model 2).

	US	EU-15	CHINA
	Coefficient (Stand Error)	Coefficient (Stand Error)	Coefficient (Stand Error)
α_i	1.20658***	3.79663***	0.999714**
	(0.377861)	(0.874004)	(0.434054)
β_1	−0.131757***	−0.216216***	0.149242***
	(0.0164047)	(0.0303647)	(0.0459104)
β_2	0.93955***	0.734233***	0.545583***
	(0.10723)	(0.104019)	(0.154954)
β_3	0.255098***	0.218422*	0.239042
	(0.0871344)	(0.119173)	(0.144152)
Sum of squared resid	0.002239	0.003498	0.02107
Adjusted R-Squared	0.952587	0.923191	0.993731
Durbin h-statistics	0.083552	1.521935	3.016924

Confidence interval: *** represents 99%, **95% and *90% confidence levels.

confirm that the measures taken by the EU-15 in the fight against climate change are on the right track and, although the results are still insufficient, the EU-15 outcomes outperform the US results. This is consistent with the leadership role assumed by the EU-15 on environmental issues.

The model developed in this work shows that the action on innovation helps to reduce CO_2 emissions, particularly in developed economies. Policy makers should enhance innovation at both the public and private levels.

5. Conclusions

Our results should be considered within the literature on innovation and environmental policies. In particular, this paper has tried to assess the extent to which aggregate R&D expenditure affects CO_2 emissions in the US, EU-15 and China for the period 1990–2013. For this, the estimation of an econometric regression by OLS has been done using as independent variables the aggregate expenditure in R&D and the final energy consumption as a proxy variable to economic growth.

The results obtained support the hypothesis that the aggregate expenditure on R&D contributes positively to the reduction of CO_2 emissions in the EU-15 and the US. This result shows that the consideration of aggregate spending on innovation is favourable in the fight against climate change, beyond the fact that the priority objective of innovation is not the environment. This reveals that the net result of the direct and indirect effects (rebound effect, spillover effect) of innovation help to solve the problem of CO_2 emissions. It is, therefore, appropriate to reinforce the spillover effect and to reduce the rebound effect of knowledge on the reduction of carbon emissions.

The outcomes also show that the corrective effect on CO_2 emissions is higher in the EU-15 than in the US. This result is consistent with the strategy followed by both regions towards the environment. The European clear commitment to control and reduce CO_2 emissions since the signing of the Kyoto Protocol guarantees clear and certain environmental policy objectives, a certainty that induces governments and companies to innovate more responsibly with climate change. In contrast, the US strategy has been less firm and later as shown by the lower coefficient.

Regarding the energy consumption, the empirical results show that this variable is positively linked to the growth of CO_2 emissions so that increases in energy consumption translate into increases in pollutant emissions. In the EU-15 the effect of this variable is lower than in the case of the US, where the energy consumption is more polluting.

For the correction of the autocorrelation problems, the endogenous variable displaced by one period was introduced as an explanatory variable. This modification has not been satisfactory in the case of China, possibly due to the differential characteristics of its economy and its less concern about the environmental problems. The inclusion of the endogenous variable with a delay captures the influence of past emissions in current ones, collecting, indirectly, the measures carried out in each region to reduce emissions. In the case of the EU-15 a lesser reliance on past emissions it is also observed, corroborating the leadership taken by Europe in the fight against climate change.

It should be noted that, despite the positive impact of innovation on the environment, it is not sufficient to offset the negative effect of energy consumption. These results indicate, on the one hand, the need to devote more resources (public and private) to direct promotion of innovation and, secondly, the need to carry out complementary measures to innovation aimed at achieving a sustainable development.

Based on the above conclusions, we identified a number of implications for policymakers related to reducing carbon emissions. It is crucial that governments encourage enterprises to carry out innovative activities independently. It is also necessary to increase public efforts on R&D. Meanwhile, more actions are needed to achieve a decoupling between energy consumption and CO_2 emissions.

As for the relevant research in the future, there is still much work to be done: due to the limits of data availability, this paper uses data from three regions since 1990 to 2013. In the future, further studies can be conducted across a longer time period or with a wider research scope. It would be very interesting to carry out a new analysis using data panel techniques, which would require increasing significantly the number of cases (countries or regions). Regarding the period of time it would be interesting to separate the analysis before and after the EU-ETS was adopted.

As innovation comes from public and private sectors, it also will be very interesting to assess the different impact of both. In this case, beside the R&D expenditure (public innovation) a new explanatory variable to be included would be the number of patents (private innovation). As private and public innovation are not evenly distributed among countries, it will be interesting to explore the differences and similarities in the mechanism and performance of environmental innovation in a future cross-national comparative analysis among, for example the US, India and China.

List of acronyms

AAGR	Average annual growth rate
EKC	Environmental Kuznets Curve
ETS	Emissions Trading System
EU-15	European Union-15
GDP	Gross Domestic Product
GHG	Green House Gas
IEA	International Energy Agency
OECD	Organization for Economic Cooperation and Development
OLS	Ordinary Least Square
R&D	Research and development
R&D&I	Research and development and innovation
PPP	Purchasing Power Parity
TOE	Tonnes of Oil Equivalent
US	United States of America

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